

The third type of fermion mixing and indirect limits on the Pati–Salam leptoquark mass

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Abstract

The low-energy manifestations of a minimal extension of the electroweak standard model based on the quark-lepton symmetry $SU(4)_V \otimes SU(2)_L \otimes G_R$ of the Pati–Salam type are analyzed. Given this symmetry the third type of mixing in the interactions of the $SU(4)_V$ leptoquarks with quarks and leptons is shown to be required. An additional arbitrariness of the mixing parameters could allow, in principle, to decrease noticeably the indirect lower bound on the vector leptoquark mass originated from the low-energy rare processes, strongly suppressed in the standard model.

1 Introduction

While the LHC methodically examines the energy scale of the electroweak theory and above, it is time to recall the two criteria for evaluating a physical theory, mentioned by A. Einstein [1]. The first point of view is obvious: a theory must not contradict empirical facts, and it is called the “external confirmation”. The test of this criterion both for the standard model and its various extensions is now engaged in the LHC. The second point of view called the “inner perfection” of the theory, may be very important to refine the search area for new physics.

All existing experimental data in particle physics are in good agreement with the standard model predictions. However, the problems exist which could not be resolved within the standard model and it is obviously not a complete or final theory. It is unquestionable that the standard model should be the low-energy limit of some higher symmetry. The question is what could be this symmetry. And the main question is, what is the mass scale of this symmetry restoration. A gloomy prospect is the restoration of this higher symmetry at once on a very high mass scale, the so-called gauge desert. A concept of a consecutive symmetry restoration is much more attractive. It looks natural in this case to suppose a correspondence of the hierarchy of symmetries and the hierarchy of the mass scales of their restoration. Now we are on the first step of some stairway of symmetries and we try to guess what could be the next one. If we consider some well-known higher symmetries from this point of view, two questions are pertinent. First, isn’t the supersymmetry [2] as the symmetry of bosons and fermions, higher than the symmetry within the fermion sector, namely, the quark-lepton symmetry [3], or the symmetry within the boson sector, namely, the left-right symmetry [4–7]? Second, wouldn’t the supersymmetry restoration be connected with a higher mass scale than the others? The recent searches for supersymmetry carried out at the Tevatron and the LHC colliders [8] shown that no significant deviations from the standard model predictions have been found, the vast parameter space available for supersymmetry has been substantially reduced and the most

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probable scenarios predicted by electroweak precision tests are now excluded or under some constraints after the new stringent limits.

We should like to analyse a possibility when the quark-lepton symmetry is the next step beyond the standard model. Along with the “inner perfection” argument for this theory, there exists a direct evidence in favor of it. The puzzle of fermion generations is recognized as one of the most outstanding problems of present particle physics, and may be the main justification for the need to go beyond the standard model. Namely, the cancellation of triangle axial anomalies which is necessary for the standard model to be renormalized, requires that fermions be grouped into generations. This association provides an equation $\sum_f T_{3f} Q_f^2 = 0$, where the summation is taken over all fermions of a generation, both quarks of three colors and leptons, T_{3f} is the 3d component of the weak isospin, and Q_f is the electric charge of a fermion. Due to this equation, the divergent axial-vector part of the triangle $Z\gamma\gamma$ diagram with a fermion loop vanishes.

The model where a combination of quarks and leptons into generations looked the most natural, proposed by J.C. Pati and A. Salam [3] was based on the quark-lepton symmetry. The lepton number was treated in the model as the fourth color. As the minimal gauge group realizing this symmetry, one can consider the semi-simple group $SU(4)_V \otimes SU(2)_L \otimes G_R$. To begin with, one can take the group $U(1)_R$ as G_R . The fermions were combined into the fundamental representations of the $SU(4)_V$ subgroup, the neutrinos with the *up* quarks and the charged leptons with the *down* quarks:

$$\begin{pmatrix} u^1 \\ u^2 \\ u^3 \\ \nu \end{pmatrix}_i, \quad \begin{pmatrix} d^1 \\ d^2 \\ d^3 \\ \ell \end{pmatrix}_i, \quad i = 1, 2, 3 \dots (?) , \quad (1)$$

where the superscripts 1,2,3 number colors and the subscript i numbers fermion generations, i.e. u_i denotes u, c, t, \dots and d_i denotes d, s, b, \dots .

The left-handed fermions form fundamental representations of the $SU(2)_L$ subgroup:

$$\begin{pmatrix} u^c \\ d^c \end{pmatrix}_L, \quad \begin{pmatrix} \nu \\ \ell \end{pmatrix}_L. \quad (2)$$

One should keep in mind that when considering the mass eigenstates, it is necessary to take into account the mixing of fermion states (1), (2), to be analysed below.

Let us remind that such an extension of the standard model has a number of attractive features.

1. As it was mentioned above, definite quark-lepton symmetry is necessary in order that the standard model be renormalized: cancellation of triangle anomalies requires that fermions be grouped into generations.
2. There is no proton decay because the lepton charge treated as the fourth color is strictly conserved.
3. Rigid assignment of quarks and leptons to representations (1) leads to a natural explanation for a fractional quark hypercharge. Indeed, the traceless 15-th generator T_{15}^V of the $SU(4)_V$ subgroup can be represented in the form

$$T_{15}^V = \sqrt{\frac{3}{8}} \text{diag} \left(\frac{1}{3}, \frac{1}{3}, \frac{1}{3}, -1 \right) = \sqrt{\frac{3}{8}} Y_V. \quad (3)$$

It is remarkable that the values of the standard model hypercharge of the left-handed quarks and leptons combined into the $SU(2)_L$ doublets turn out to be placed on the diagonal. Let us call it the vector hypercharge, Y_V , and assume that it belongs to both the left- and right-handed fermions.

4. Let us suppose that $G_R = U(1)_R$. The well-known values of the standard model hypercharge of the left and right, and *up* and *down* quarks and leptons are:

$$Y_{SM} = \left\{ \begin{array}{ll} \begin{pmatrix} \frac{1}{3} \\ \frac{1}{3} \end{pmatrix} & \text{for } q_L; \quad \begin{pmatrix} -1 \\ -1 \end{pmatrix} & \text{for } \ell_L \\ \begin{pmatrix} \frac{4}{3} \\ -\frac{2}{3} \end{pmatrix} & \text{for } q_R; \quad \begin{pmatrix} 0 \\ -2 \end{pmatrix} & \text{for } \ell_R \end{array} \right\}. \quad (4)$$

Then, from the equation $Y_{SM} = Y_V + Y_R$, taking Eq. (3) into account, one obtains that the values of the right hypercharge Y_R occur to be equal ± 1 for the *up* and *down* fermions correspondingly, both quarks and leptons. It is tempting to interpret this circumstance as the indication that the right-hand hypercharge is the doubled third component of the right-hand isospin. Thus, the subgroup G_R may be $SU(2)_R$.

“Under these circumstances one would be surprised if Nature had made no use of it”, as P. Dirac wrote on another occasion [9].

The most exotic object of the Pati–Salam type symmetry is the charged and colored gauge X boson named leptoquark. Its mass M_X should be the scale of breaking of $SU(4)_V$ to $SU(3)_c$. Bounds on the vector leptoquark mass are obtained both directly and indirectly, see Ref. [10]. The direct search [11] for vector leptoquarks using $\tau^+ \tau^- b \bar{b}$ events in $p\bar{p}$ collisions at $E_{cm} = 1.96$ TeV have provided the lower mass limit at a level of 250–300 GeV, depending on the coupling assumed. Much more stringent indirect limits are calculated from the bounds on the leptoquark-induced four-fermion interactions, which are obtained from low-energy experiments. There is an extensive series of papers where such indirect limits on the vector leptoquark mass were estimated, see e.g. Refs. [12–22]. The most stringent bounds [10] were obtained from the data on the $\pi \rightarrow e\nu$ decay and from the upper limits on the $K_L^0 \rightarrow e\mu$ and $B^0 \rightarrow e\tau$ decays. However, those estimations were not comprehensive because the phenomenon of a mixing in the lepton-quark currents was not considered there. It will be shown that such a mixing inevitably occurs in the theory.

An important part of the model under consideration is its scalar sector, which also contains exotic objects such as scalar leptoquarks. We do not concern here the scalar sector, which could be much more ambiguous than the gauge one. Such an analysis can be found e.g. in Refs. [21–23].

The paper is organized as follows. In Sec. 2, it is argued that three types of fermion mixing inevitably arise at the loop level if initially fermions are taken without mixing. The effective four-fermion Lagrangian caused by the leptoquark interactions with quarks and leptons is presented in Sec. 3. In Sec. 4, we update the constraints on the parameters of the scheme which were obtained in our recent paper [24] on a base of the data from different low-energy processes which are strongly suppressed or forbidden in the standard model. The updating of the constraint on the vector leptoquark mass is made in Sec. 6 basing on a new data from CMS and LHCb Collaborations on the rare decays $B_{d,s}^0 \rightarrow \mu^+ \mu^-$ [25–27].

2 The third type of fermion mixing

As the result of the Higgs mechanism in the Pati–Salam model, fractionally charged colored gauge X -bosons, vector leptoquarks appear. Leptoquarks are responsible for transitions between quarks and leptons. The scale of the breakdown of $SU(4)_V$ symmetry to $SU(3)_c$ is the leptoquark mass M_X . The three fermion generations are grouped into the following $\{4, 2\}$

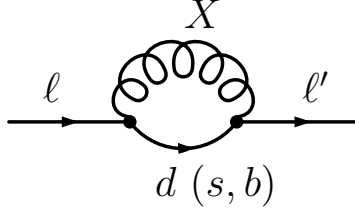


Figure 1: Feynman diagram illustrating the appearance of fermion mixings.

representations of the $SU(4)_V \otimes SU(2)_L$ group:

$$\begin{pmatrix} u^c & d^c \\ \nu & \ell \end{pmatrix}_i \quad (i = 1, 2, 3). \quad (5)$$

where c is the color index to be further omitted. It is known that there exists the mixing of quarks in weak charged currents, which is described by the Cabibbo-Kobayashi-Maskawa matrix. Therefore, at least one of the states in (5), u or d , is not diagonal in mass. It can easily be seen that, because of mixing that arises at the loop level, none of the components is generally a mass eigenstate. As usual, we assume that all the states in (5), with the exception of d , are initially diagonal in mass. This leads to nondiagonal transitions $\ell \rightarrow X + d(s, b) \rightarrow \ell'$ through a quark-leptoquark loop, see Fig. 1. As this diagram is divergent, the corresponding counterterm should exist at the tree level. This means that the lepton states ℓ in (5) are not the mass eigenstates, and there is mixing in the lepton sector. Other nondiagonal transitions arise in a similar way. Hence, in order that the theory be renormalizable, it is necessary to introduce all kinds of mixing even at the tree level. As all the fermion representations are identical, they can always be regrouped in such a way that one state is diagonal in mass. The most natural way is to diagonalize charged leptons. In this case, fermion representations can be written in the form

$$\begin{pmatrix} u & d \\ \nu & \ell \end{pmatrix}_\ell = \begin{pmatrix} u_e & d_e \\ \nu_e & e \end{pmatrix}, \quad \begin{pmatrix} u_\mu & d_\mu \\ \nu_\mu & \mu \end{pmatrix}, \quad \begin{pmatrix} u_\tau & d_\tau \\ \nu_\tau & \tau \end{pmatrix}. \quad (6)$$

Here, the quarks and neutrinos subscripts $\ell = e, \mu, \tau$ label the states which are not mass eigenstates and which enter into the same representation as the charged lepton ℓ :

$$\nu_\ell = \sum_i \mathcal{K}_{\ell i} \nu_i, \quad u_\ell = \sum_p \mathcal{U}_{\ell p} u_p, \quad d_\ell = \sum_n \mathcal{D}_{\ell n} d_n. \quad (7)$$

Here, $\mathcal{K}_{\ell i}$ is the unitary leptonic mixing matrix by Pontecorvo-Maki-Nakagawa-Sakata. The matrices $\mathcal{U}_{\ell p}$ and $\mathcal{D}_{\ell n}$ are the unitary mixing matrices in the interactions of leptoquarks with the up and $down$ fermions correspondingly, both quarks and leptons. The states ν_i , u_p and d_n are the mass eigenstates:

$$\begin{aligned} \nu_i &= (\nu_1, \nu_2, \nu_3), \\ u_p &= (u_1, u_2, u_3) = (u, c, t), \\ d_n &= (d_1, d_2, d_3) = (d, s, b). \end{aligned} \quad (8)$$

Thus, there are generally three types of mixing in this scheme.

In our notation, the well-known Lagrangian describing the interaction of charge weak currents with W -bosons takes the form

$$\begin{aligned} \mathcal{L}_W &= \frac{g}{2\sqrt{2}} [(\bar{\nu}_\ell O_\alpha \ell) + (\bar{u}_\ell O_\alpha d_\ell)] W_\alpha^\dagger + \text{h.c.} \\ &= \frac{g}{2\sqrt{2}} [\mathcal{K}_{\ell i}^* (\bar{\nu}_i O_\alpha \ell) + \mathcal{U}_{\ell p}^* \mathcal{D}_{\ell n} (\bar{u}_p O_\alpha d_n)] W_\alpha^\dagger + \text{h.c.}, \end{aligned} \quad (9)$$

where g is the constant of the $SU(2)_L$ group and $O_\alpha = \gamma_\alpha (1 - \gamma_5)$. It follows that the standard Cabibbo–Kobayashi–Maskawa matrix is $V = \mathcal{U}^\dagger \mathcal{D}$. This is the only available information about the matrices \mathcal{U} and \mathcal{D} of mixing in the leptoquark sector. The matrix \mathcal{K} describing a mixing in the lepton sector is the subject of intensive experimental studies.

Following the spontaneous breakdown of the $SU(4)_V$ symmetry to $SU(3)_c$ on the scale of M_X , six massive vector bosons forming three charged colored leptoquarks, decouple from the 15-plet of gauge fields. The interaction of these leptoquarks with fermions has the form

$$\mathcal{L}_X = \frac{g_S(M_X)}{\sqrt{2}} \left[\mathcal{D}_{\ell n} (\bar{\ell} \gamma_\alpha d_n^c) + \left(\mathcal{K}^\dagger \mathcal{U} \right)_{ip} (\bar{\nu}_i \gamma_\alpha u_p^c) \right] X_\alpha^c + \text{h.c.}, \quad (10)$$

where the color superscript c is written explicitly once again. The coupling constant $g_S(M_X)$ is expressed in terms of the strong-interaction constant α_S on the scale of the leptoquark mass M_X as $g_S^2(M_X)/4\pi = \alpha_S(M_X)$.

3 Effective Lagrangian with allowance for QCD corrections

If the momentum transfer satisfies the condition $q^2 \ll M_X^2$, the Lagrangian (10) leads to the effective four-fermion vector-vector interaction between quarks and leptons. By applying the Fierz transformation, we can isolate the lepton and quark currents (scalar, pseudoscalar, vector and axial-vector currents) in the effective Lagrangian. In constructing the effective Lagrangian of leptoquark interactions, it is necessary to take into account the QCD corrections, which can easily be estimated, see e.g. Refs. [28,29]. In the case under study, we can use the approximation of leading logarithms because $\ln(M_X/\mu) \gg 1$, where $\mu \sim 1$ GeV is the typical hadronic scale. As the result of taking the QCD corrections into account, the scalar and pseudoscalar coupling constants acquire the enhancement factor

$$Q(\mu) = \left(\frac{\alpha_S(\mu)}{\alpha_S(M_X)} \right)^{4/\bar{b}}, \quad (11)$$

where $\alpha_S(\mu)$ is the strong-interaction constant on the scale μ , $\bar{b} = 11 - 2/3(\bar{n}_f)$, and \bar{n}_f is the mean number of quark flavors on the scales $\mu^2 \leq q^2 \leq M_X^2$; for $M_X^2 \gg m_t^2$, we have $\bar{b} \simeq 7$.

Further we investigate the contribution to low-energy processes from the interaction Lagrangian (10) involving leptoquarks and find constraints on the parameters of the scheme from available experimental data. As the analysis shows, the most stringent constraints on the vector-leptoquark mass M_X and on the elements of the mixing matrix \mathcal{D} follow from the data on rare π and K meson decays.

Possible constraints on the masses and coupling constants of vector leptoquarks from experimental data on rare π and K decays were analyzed in Refs. [12–22]. One approach [12,14,15] was based on using the phenomenological model-independent Lagrangians describing the interactions of leptoquarks with quarks and leptons. Pati–Salam quark-lepton symmetry was considered in Refs. [13,16–22]. QCD corrections were included into an analysis in Refs. [16–18]. The authors of Ref. [16] considered the possibility of mixing in quark-lepton currents, but they analyzed only specific cases in which each charged lepton is associated with one quark generation. In our notation, this corresponds to the matrices \mathcal{D} that are obtained from the unit matrix by making all possible permutation of columns.

In the description of the π - and K -meson interactions, it is sufficient to retain only the scalar and pseudoscalar coupling constants in the effective Lagrangian. Really, these couplings are more significant in the amplitudes, because they are enhanced, first, by QCD corrections, and second, by the smallness of the current-quark masses arising in the amplitude denominators.

The corresponding part of the effective Lagrangian can be represented as

$$\begin{aligned}
\Delta\mathcal{L}_{\pi,K} = & -\frac{2\pi\alpha_S(M_X)}{M_X^2} Q(\mu) \left[\mathcal{D}_{\ell n} \left(\mathcal{U}^\dagger \mathcal{K} \right)_{pi} (\bar{\ell} \gamma_5 \nu_i) (\bar{u}_p \gamma_5 d_n) + \text{h.c.} - (\gamma_5 \rightarrow 1) \right] \\
& - \frac{2\pi\alpha_S(M_X)}{M_X^2} Q(\mu) \left[\mathcal{D}_{\ell n} \mathcal{D}_{\ell' n'}^* (\bar{\ell} \gamma_5 \ell') (\bar{d}_{n'} \gamma_5 d_n) \right. \\
& \left. + \left(\mathcal{K}^\dagger \mathcal{U} \right)_{ip} \left(\mathcal{U}^\dagger \mathcal{K} \right)_{p'i'} (\bar{\nu}_i \gamma_5 \nu_{i'}) (\bar{u}_{p'} \gamma_5 u_p) - (\gamma_5 \rightarrow 1) \right].
\end{aligned} \tag{12}$$

This Lagrangian contributes to the rare π , K , τ and B decays, which are strongly suppressed or forbidden in the standard model. For the τ and B decays, this Lagrangian is not enough, and a part with the product of axial-vector currents should be added.

4 Constraints on the parameters of the scheme from low-energy processes

In our recent paper [24], we have performed a detailed analysis of a large set of experimental data on different low-energy processes which are strongly suppressed or forbidden in the standard model. The constraints on the vector leptoquark mass were obtained. In Table 1, the most stringent constraints of Ref. [24] are summarized. All the constraints involve the elements of the unknown unitary mixing matrix \mathcal{D} :

$$\mathcal{D}_{\ell n} = \begin{pmatrix} \mathcal{D}_{ed} & \mathcal{D}_{es} & \mathcal{D}_{eb} \\ \mathcal{D}_{\mu d} & \mathcal{D}_{\mu s} & \mathcal{D}_{\mu b} \\ \mathcal{D}_{\tau d} & \mathcal{D}_{\tau s} & \mathcal{D}_{\tau b} \end{pmatrix}. \tag{13}$$

The possibility was analysed in Ref. [24] for the constraints on the vector leptoquark mass M_X to be much weaker than the numbers in Table 1. The case was considered when the elements \mathcal{D}_{ed} and \mathcal{D}_{es} are small enough, to eliminate the most strong restriction arising from the limit on the decays $K_L^0 \rightarrow e^\pm \mu^\mp$. For evaluation, these elements were taken to be zero. Given the unitarity of the matrix \mathcal{D} , this meant that $\mathcal{D}_{eb} = 1$, and $\mathcal{D}_{\mu b} = \mathcal{D}_{\tau b} = 0$. The remaining (2×2) -matrix was parameterized by one angle. The insertion of the phase factor allowed to eliminate the restriction arising from the limit on $Br(K_L^0 \rightarrow \mu^+ \mu^-)$ which contained the real part of the \mathcal{D} matrix elements product. The \mathcal{D} matrix was taken in the form:

$$\mathcal{D}_{\ell n} \simeq \begin{pmatrix} 0 & 0 & 1 \\ \cos \varphi & i \sin \varphi & 0 \\ i \sin \varphi & \cos \varphi & 0 \end{pmatrix}. \tag{14}$$

The constraints on the vector leptoquark mass and the φ angle arising from Table 1 took the form:

i) $B^0 \rightarrow e^+ \mu^-$

$$M_X > 55 \text{ TeV} |\cos \varphi|^{1/2}, \tag{15}$$

ii) $B_s^0 \rightarrow e^+ \mu^-$

$$M_X > 41 \text{ TeV} |\sin \varphi|^{1/2}. \tag{16}$$

Combining these constraints, the limit on the vector leptoquark mass was obtained [24]:

$$M_X > 38 \text{ TeV}. \tag{17}$$

Table 1: Constraints on the leptoquark mass and on the elements of the \mathcal{D} matrix from experimental data on rare decays.

Experimental limit	Ref.	Bound
$Br(K_L^0 \rightarrow e^\pm \mu^\mp) < 4.7 \times 10^{-12}$	[30]	$\frac{M_X}{ \mathcal{D}_{ed}\mathcal{D}_{\mu s}^* + \mathcal{D}_{es}\mathcal{D}_{\mu d}^* ^{1/2}} > 2100 \text{ TeV}$
$Br(K_L^0 \rightarrow \mu^+ \mu^-) = (6.84 \pm 0.11) \times 10^{-9}$	[31, 32]	$\frac{M_X}{ \text{Re}(\mathcal{D}_{\mu d}\mathcal{D}_{\mu s}^*) ^{1/2}} > 1100 \text{ TeV}$
$Br(B^0 \rightarrow e^+ \mu^-) < 6.4 \times 10^{-8}$	[33]	$\frac{M_X}{ \mathcal{D}_{\mu d}\mathcal{D}_{eb} ^{1/2}} > 55 \text{ TeV}$
$Br(B^0 \rightarrow \mu^+ \mu^-) < 1.5 \times 10^{-8}$	[34]	$\frac{M_X}{ \mathcal{D}_{\mu d}\mathcal{D}_{\mu b} ^{1/2}} > 79 \text{ TeV}$
$Br(B_s^0 \rightarrow e^+ \mu^-) < 2.0 \times 10^{-7}$	[33]	$\frac{M_X}{ \mathcal{D}_{\mu s}\mathcal{D}_{eb} ^{1/2}} > 41 \text{ TeV}$
$Br(B_s^0 \rightarrow \mu^+ \mu^-) < 4.2 \times 10^{-8}$	[35]	$\frac{M_X}{ \mathcal{D}_{\mu s}\mathcal{D}_{\mu b} ^{1/2}} > 61 \text{ TeV}$

5 Different mixings for left-handed and right-handed fermions

We have considered a possibility when the quark-lepton symmetry was the next step beyond the standard model. Then the left-right symmetry which is believed to exist in Nature, should restore at higher mass scale. But this means that the left-right symmetry should be already broken at the scale M_X . It is worthwhile to consider the matrices $\mathcal{D}^{(L)}, \mathcal{U}^{(L)}$ and $\mathcal{D}^{(R)}, \mathcal{U}^{(R)}$ which are in a general case different for left-handed and right-handed fermions. This possibility and some its consequences were also considered in Refs. [19–22]. The interaction Lagrangian of leptoquarks with fermions takes the form instead of Eq. (10):

$$\begin{aligned} \mathcal{L}_X = & \frac{g_S (M_X)}{2\sqrt{2}} \left[\mathcal{D}_{\ell n}^{(L)} (\bar{\ell} O_\alpha d_n) + \mathcal{D}_{\ell n}^{(R)} (\bar{\ell} O'_\alpha d_n) \right. \\ & \left. + \left(\mathcal{K}^{(L)\dagger} \mathcal{U}^{(L)} \right)_{ip} (\bar{\nu}_i O_\alpha u_p) + \left(\mathcal{K}^{(R)\dagger} \mathcal{U}^{(R)} \right)_{ip} (\bar{\nu}_i O'_\alpha u_p) \right] X_\alpha + \text{h.c.}, \end{aligned} \quad (18)$$

where $O_\alpha = \gamma_\alpha (1 - \gamma_5)$, $O'_\alpha = \gamma_\alpha (1 + \gamma_5)$.

The constraints on the model parameters from experimental data on rare π and K decays in the case of different mixings take the forms presented in Table 5 of Ref. [24]. If one would wish to reduce the limits on M_X presented there from thousands and hundreds to tens of TeV by varying the elements of the $\mathcal{D}^{(L)}$ and $\mathcal{D}^{(R)}$ matrices, it seems that the elements $\mathcal{D}_{ed}^{(L)}$ and $\mathcal{D}_{ed}^{(R)}$ should be taken small in any case. If one takes them for evaluation be zero, the most strong restriction from the limit on $Br(K_L^0 \rightarrow e^\pm \mu^\mp)$ acquires the form:

$$\frac{M_X}{\left(\left| \mathcal{D}_{es}^{(L)} \mathcal{D}_{\mu d}^{(R)} \right|^2 + \left| \mathcal{D}_{es}^{(R)} \mathcal{D}_{\mu d}^{(L)} \right|^2 \right)^{1/4}} > 1770 \text{ TeV}. \quad (19)$$

There are two possibilities to eliminate this bound, which we call the symmetric and the asymmetric cases.

The *symmetric case* is realized when both of the matrices $\mathcal{D}^{(L)}$ and $\mathcal{D}^{(R)}$ are taken in the form of Eq. (14) with the angles φ_L and φ_R . In this case the restriction from the limit on $Br(K_L^0 \rightarrow \mu^+ \mu^-)$ takes the form:

$$M_X > 780 \text{ TeV} |\sin(\varphi_L - \varphi_R)|^{1/2}. \quad (20)$$

To eliminate this bound, the angles should be close to each other or differ by π , in any case we come back to the result (17).

The *asymmetric case* is realized when the matrices are taken in the form:

$$\mathcal{D}_{\ell n}^{(L)} \simeq \begin{pmatrix} 0 & \cos \chi_L & \sin \chi_L \\ 0 & -\sin \chi_L & \cos \chi_L \\ 1 & 0 & 0 \end{pmatrix}, \quad \mathcal{D}_{\ell n}^{(R)} \simeq \begin{pmatrix} 0 & 0 & 1 \\ 0 & 1 & 0 \\ 1 & 0 & 0 \end{pmatrix}. \quad (21)$$

As the analysis shows [24], the most stringent constraints arise from the following limits on the branching ratios of the processes:

i) $B_s^0 \rightarrow \mu^+ \mu^-$

$$M_X > 51 \text{ TeV} |\cos \chi_L|^{1/2}, \quad (22)$$

ii) $B_s^0 \rightarrow e^+ \mu^-$

$$M_X > 41 \text{ TeV} |\sin \chi_L|^{1/2}. \quad (23)$$

From these constraints, the limit was obtained [24] on the vector leptoquark mass from low-energy processes in the case of different mixing matrices for left-handed and right-handed fermions, which coincided, with a good accuracy, with the limit (17) obtained in the left-right-symmetric case:

$$M_X > 38 \text{ TeV}. \quad (24)$$

6 Updated constraints from the LHC data

The updating of the constraint on the vector leptoquark mass is based on a new data from CMS and LHCb Collaborations on the rare decays $B_{d,s}^0 \rightarrow \mu^+ \mu^-$ [25–27], which are presented in Table 2.

These new data improve the constraints obtained in the asymmetric case (21), namely, the data of the LHCb Collaboration on the decay $B_s^0 \rightarrow \mu^+ \mu^-$ provide, instead of (22):

$$M_X > 94 \text{ TeV} |\cos \chi_L|^{1/2}. \quad (25)$$

Combining this bound with Eq. (23), one obtains the final limit on the vector leptoquark mass in the case of different mixing matrices for left-handed and right-handed fermions:

$$M_X > 41 \text{ TeV}. \quad (26)$$

7 Conclusion

Thus, the detailed analysis of the available experimental data on rare decays yields constraints on the vector leptoquark mass that always involve the elements of the unknown mixing matrix \mathcal{D} . Combining the most strong constraints from the experimental data on the low-energy processes, presented in Tables 1 and 2, we have obtained in the case of identical mixings for left-handed and right-handed fermions the following lowest limit on the vector leptoquark mass: $M_X > 38 \text{ TeV}$. The lowest limit obtained in the asymmetric case (21) of different mixing matrices for left-handed and right-handed fermions appears to be: $M_X > 41 \text{ TeV}$.

Table 2: Constraints on the model parameters from new data of the CMS and LHCb Collaborations on the rare decays $B_{d,s}^0 \rightarrow \mu^+ \mu^-$ (90 % C.L.)

Experimental limit	Ref.	Bound
$Br(B^0 \rightarrow \mu^+ \mu^-) < 1.4 \times 10^{-9}$	CMS [25]	$\frac{M_X}{ \mathcal{D}_{\mu d} \mathcal{D}_{\mu b} ^{1/2}} > 143 \text{ TeV}$
$Br(B_s^0 \rightarrow \mu^+ \mu^-) < 6.4 \times 10^{-9}$	CMS [25]	$\frac{M_X}{ \mathcal{D}_{\mu s} \mathcal{D}_{\mu b} ^{1/2}} > 98 \text{ TeV}$
$Br(B^0 \rightarrow \mu^+ \mu^-) < 0.81 \times 10^{-9}$	LHCb [26]	$\frac{M_X}{ \mathcal{D}_{\mu d} \mathcal{D}_{\mu b} ^{1/2}} > 164 \text{ TeV}$
$Br(B_s^0 \rightarrow \mu^+ \mu^-) < 3.8 \times 10^{-9}$	LHCb [26]	$\frac{M_X}{ \mathcal{D}_{\mu s} \mathcal{D}_{\mu b} ^{1/2}} > 112 \text{ TeV}$

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